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OXIDATION CHARACTERISTICS OF VARIOUS STRUCTURAL MATERIALS FOR RAMJETS AND HEAT EXCHANGERS

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OXIDATION CHARACTERISTICS OF
VARIOUS STRUCTURAL MATERIALS
FOR RAMJETS AND HEAT EXCHANGERS

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Project 281

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I. SUMMARY

Environmental tests were made to determine the oxidation characteristics of various sheet materials which exhibited a strong potential for use in ramjet engine and/or heat exchanger structures. The sheet materials tested were Rene' 41, L-605, Hastelloy C, Types 316L and 321 stainless steel, 6061-T6 aluminum, and A110-AT titanium alloys.

These materials were evaluated over anticipated service temperature ranges for 5, 25, and 50-hour oxidation exposure periods. Exposure temperatures for the first five of these alloys were 1200°, 1500°, and 1800°F. For the last two alloys, the exposure temperatures were 350°, 500°, and 650°F; and 800°, 1000°, and 1200°F, respectively. Test specimen thicknesses ranged from 0.025 to 0.033 inch.

Test results indicate that Rene' 41 and L-605 alloys are serviceable at 1500°F for 50 hours without any effect or perceptible attack on the alloys. Hastelloy C is satisfactory for long time operation at 1800°F. Types 316L and 321 stainless steel may be used at 1500°F for varying time periods. The 6061-T6 aluminum alloy retains good mechanical properties at 350°F and excellent oxidation resistance to 650°F for 50 hours. A110-AT titanium is satisfactory at 1200°F for time periods up to 50 hours. The characteristics of these alloys for the temperature and exposure conditions noted may decline noticeably as the thickness of the materials are reduced.

II. INTRODUCTION

During 1961, a program was conducted at Marquardt to evaluate alloys which were potentially most suitable for ramjet and heat exchanger structures. Mechanical property tests were performed to generate short time tensile, yield, elongation, creep, and stress rupture data. These tests were very successful from a preliminary selection standpoint and yielded much valuable information. Time did not permit extension of the testing program to include environmental exposure (oxidizing) reaction over extended time periods at temperature.

In consideration of the fact that severe oxidation in service can lead to catastrophic structural failure, a program was conducted during 1962 to determine the reaction of selected candidate alloys upon exposure in an oxidizing environment for time periods up to 50 hours at maximum predicted service temperatures.

The materials selected were Rene' 41, L-605, Hastelloy C, Types 316L and 321 stainless steel, 6061-T6 aluminum, and A110-AT titanium alloys. Exposure temperatures ranged from 350° to 1800°F, depending on the alloy. Specimens were removed from the test environment at 5, 25, and 50 hour intervals to measure the percentage of oxide penetration. Mechanical property tests and metallographic examinations were made to determine the base metal degradation and the resulting metallurgical structure. Comparisons were then made between exposed and unexposed control specimens. Test results and analyses are reported herein.

III. TEST PROCEDURES

Prior to initiation of oxidation exposure periods, short time tensile tests were conducted at room temperature for all of the alloys being tested in this program. The results of these tests (which are summarized in Table I) are representative of material strengths listed in published data.

Suitable quantities of each material and thickness were procured, and tensile specimens were prepared. Of the seven alloys tested, only two were heat treatable (Rene' 41 and 6061-T4). The Rene' 41 alloy was solution heat treated at 1950°F for 30 minutes in vacuum, then aged at 1400°F for 16 hours. The 6061-T4 alloy was aged to the -T6 condition in accordance with specification MIL-H-6088.

Photomicrographs (at 1000 X) were made of unexposed base metal specimens. Additional photomicrographs were made of specimens removed from the test environment after exposures for 5, 25, and 50 hours.

Tensile tests were performed on specimens removed from the test environment after the 5, 25, and 50 hour exposures. The levels of temperature exposure which were used correspond with the elevated temperature range potentially required of each alloy in service.

The specimens were exposed in a small laboratory furnace which was modified to allow a stream of filtered air to flow continuously into the exposure area.

Before exposure, all specimens were weighed to the nearest 0.01 gram and their thicknesses were measured to the nearest 0.0001 inch. After exposure periods, thickness measurements were made in identical locations on each specimen.

IV. TEST RESULTS

Test results showing the effect of oxidation exposure and aging on tensile properties are presented in Tables II through VIII. The ultimate tensile and yield strengths are shown graphically in Figures 1 through 7.

Also presented in Tables II through VIII are tabular data showing changes in weight and thickness for the various alloys due to oxidation exposure.

Photomicrographs showing the microstructure of the alloys after oxidation exposure are presented in Figures 8 through 14.

V. DISCUSSION OF RESULTS

A. Mechanical Properties

Table II presents data generated from environmental exposure and tesing of Rene' 41 specimens. The results are compared with control specimens. Changes in weight and thicknesses are noted for each temperature and exposure period. At the 1200° and 1500°F exposure temperatures there was no significant change in weight or thickness. At 1800°F, the maximum scaling noted was 1.4 mils after 50 hours. Reductions in tensile ultimate and yield strengths from control specimen values were 20 and 30%, respectively, at 1800°F. Elongation values exhibited at 1800°F showed improvement for exposed versus non-exposed specimens. The decrease of ultimate tensile and yield strength plus elongation value increase at 1800°F can be attributed to partial resolutioning of the Rene' 41 alloy material.

Table III presents data generated from exposure and testing of L-605 alloy. No significant changes in weight and thicknesses were noted for any of the exposure temperatures. Elongation at 1500° and 1800°F was noticeably higher for exposed specimens and was attributed to relieving of rolling stresses induced during manufacture of the thin material.

Table IV presents data from the Hastelloy C specimens. Tensile ultimate and yield strengths were higher and elongation was lower for the 1500°F exposed specimens. This can be attributed to age hardening of the alloy. Mechanical properties exhibited at 1800°F were comparable for both exposed and unexposed specimens. No significant changes in weight or thickness were noted.

Table V presents data from the Type 316L specimens. Tensile ultimate and yield strength values exhibited at 1800°F were comparable for the exposed and control specimens and some decrease in ductility was noted for the exposed specimens. Intergranular oxide penetration occurred at the 1800°F exposure temperature, resulting in the lower elongation values.

Table VI presents data from the Type 321 stainless specimens. Results are compared with those for the control specimens. Tensile ultimate and yield strength properties of exposed specimens at 1800°F compared favorably with the values for the control specimens. Elongation values at 1800°F showed a continuing decline as the exposure times were increased, indicating the embrittling effects of intergranular penetration of oxides.

Table VII presents data generated from environmentally exposing and testing the 6061-T6 aluminum specimens. The results are compared with those for the control specimens. The most significant mechanical properties are those exhibited at 350°F, since 6061 aluminum is precipitation aged at that temperature to achieve maximum (-T6) properties. The decline of mechanical properties at 350°F after 50 hours of exposure was minor. The properties exhibited at 500°F, after only 5 hours exposure indicated a 20 to 25% decline in ultimate tensile and yield strengths. This verifies the effect of rapid overaging of the 6061-T6 alloy.

Table VIII presents data generated from environmentally exposing and testing A110-AT titanium alloy specimens. The results are compared with control specimens. The maximum exposure temperature of 1200°F is most significant because it exceeds the normally designated operational temperature of this alloy by 300°F. The values exhibited at 1200°F after 50 hour exposure were comparable with those for the unexposed specimens. This indicates that A110-AT (5AL-2.5 Sn) titanium alloy can be safely used to a temperature of 1200°F for relatively long periods without decline of properties.

B. Photomicrographs

Figures 8 to 14 are photomicrographs of exposed and unexposed alloys at various temperatures and time periods. The specimens were not etched.

VI. CONCLUSIONS

Hastelloy C alloy was the only one of the seven alloys tested that did not exhibit significant changes in mechanical and physical properties under the conditions investigated. The other alloys exhibited either a reduction in strength or a significant change of microstructure.

The data presented in this report may be considered as design allowables, but only for the conditions of temperature, time, and material thickness described herein. It is anticipated that there would be a varying reaction of thinner materials and conceivable percentagewise decline of exhibited properties after long time temperature exposures in oxidizing atmospheres.

TABLE I

SUMMARY OF TENSILE CONTROL SPECIMENS FOR OXIDATION TESTS

Test Conditions:

Material = As noted, liquid honed prior to testing
Test temperature = Room temperature
Strain rate = 0.005 in./in./min to rupture

Material	Thickness (inch)	Proportional Limit (Ksi)	0.2% Yield Strength (Ksi)	Ultimate Tensile Strength (Ksi)	Elongation in 2 inches (%)	Young's Modulus (10^6 psi)
Hastelloy C	0.025	39.5	63.7	128.2	47	29.2
	0.025	30.7	62.5	128.6	45	28.2
	0.025	45.2	70.2	125.8	44	28.2
6061-T6	0.032	26.8	37.9	43.3	10	10.8
	0.032	29.8	38.3	43.0	10	10.4
	0.032	27.5	37.0	42.7	9.5	10.2
Rene' 41 **	0.030	103.5	131.3	181.6	(10)*	29.4
	0.030	105.0	133.5	192.8	14	30.2
	0.030	98.9	130.2	190.3	14	29.0
316L Stainless	0.032	28.5	48.2	92.0	46	28.1
	0.032	20.7	40.9	92.4	46	27.7
	0.032	13.8	39.9	91.4	47	27.2
L-605	0.030	32.7	66.0	139.5	44	27.5
	0.030	34.0	68.0	138.0	43	28.6
321 Stainless	0.030	16.8	35.7	87.5	45	27.0
	0.030	16.3	32.8	88.3	48	27.6
A110AT	0.030	99.7	115.1	125.8	13.5	16.6
	0.030	89.3	115.6	126.6	14	16.4

* Broke outside gage length

** Solution treated 1950°F, 30 minutes in vacuum, aged for 16 hours at 1400°F in air

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TABLE II

EFFECT OF OXIDATION EXPOSURE ON RENE' 41 ALLOY SHEET

Test Conditions:

Oxidation Exposure = Laboratory furnace, 30 CFH shop air
Strain rates = 0.001 in./in./sec to yield
0.01 in./in./sec to rupture

Gage length = 2.0 inches
Thickness = 0.028 inch
Hold time = 5 minutes

Exposure	Change in Weight (%)	Change in Thickness (inch)	Tensile Test Temperature (°F)	Proportional Limit (Ksi)	0.2% Yield Strength (Ksi)	Ultimate Tensile Strength (Ksi)	Elongation in 2 inches (%)	Young's Modulus (10^6 psi)
None (Control)	--	--	RT	103.5	131.5	181.6	10.0*	29.4
None (Control)	--	--	RT	105.0	133.5	192.6	14.0	30.2
None (Control)	--	--	RT	98.9	130.2	190.3	14.0	29.0
None (Control)	--	--	1800	31.0	40.0	55.5	6.0	17.4
None (Control)	--	--	1800	29.0	42.6	50.1	13.0	16.3
1200°F 7 hr	0	0	1200	90.1	127.0	170.1	9.0	25.0
1200°F 25 hr	0	+0.0003	1200	88.0	127.0	167.0	9.0	25.9
1200°F 50 hr	0	+0.0002	1200	91.0	135.3	174.1	8.5	26.7
1200°F 50 hr	+0.04	0	1200	--	--	--	--	--
1200°F 50 hr	0	+0.0003	1200	--	--	--	--	--
1200°F 50 hr	0	+0.0002	1200	--	--	--	--	--
1500°F 5 hr	+0.04	+0.0002	1500	78.0	112.9	137.5	7.5	21.0
1500°F 25 hr	+0.04	+0.0003	1500	70.0	104.0	130.0	8.5	23.4
1500°F 50 hr	+0.08	+0.0006	1500	83.0	115.0	140.2	8.0	23.2
1500°F 50 hr	+0.16	+0.0002	1500	--	--	--	--	--
1500°F 50 hr	+0.12	+0.0002	1500	--	--	--	--	--
1500°F 50 hr	+0.08	+0.0003	1500	--	--	--	--	--
1800°F 5 hr	-0.49**	+0.0008**	1800	24.5	30.6	44.2	17.0	16.3
1800°F 25 hr	+0.55	+0.0011	1800	17.0	25.3	41.6	19.5	16.9
1800°F 50 hr	+0.53	+0.0012	1800	20.2	28.3	44.0	15.5	15.4
1800°F 50 hr	+0.49	+0.0014	1800	--	--	--	--	--
1800°F 50 hr	+0.56	+0.0009	1800	--	--	--	--	--
1800°F 50 hr	+0.53	+0.0010	1800	--	--	--	--	--

* Broke outside gage length
** Light green loose scale

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TABLE III

EFFECT OF OXIDATION EXPOSURE ON L-605 ALLOY SHEET

Test Condtions:

Oxidation Exposure = Laboratory furnace, 30 CFH shop air
Strain rates = 0.001 in./in./sec to yield
0.01 in./in./sec to rupture

Gage length = 2.0 inches
Thickness = 0.032 inch
Hold time = 5 minutes

Exposure	Change in Weight (%)	Change in Thickness (inch)	Tensile Test Temperature (°F)	Proportional Limit (Ksi)	0.2% Yield Strength (Ksi)	Ultimate Tensile Strength (Ksi)	Elongation in 2 inches (%)	Young's Modulus (10^6 psi)
None (Control)	--	--	RT	32.7	66.0	139.5	44	27.5
None (Control)	--	--	RT	34.0	68.0	138.0	43	28.6
None (Control)	--	--	1800	19.9	25.9	37.3	15.0	16.9
1200°F 5 hr			1200	32.4	41.8	90.0	45.0	24.1
1200°F 25 hr			1200	34.0	45.0	92.6	46.5	23.1
1200°F 50 hr	-0.03	-0.0001	1200	--	--	89.0	40.0	--
1200°F 50 hr	0	+0.0002	1200	--	--	--	--	--
1200°F 50 hr	0	+0.0003	1200	--	--	--	--	--
1200°F 50 hr	0	+0.0001	1200	--	--	--	--	--
1500°F 5 hr	+0.03	+0.0002	1500	28.5	34.0	78.0	39.0	21.0
1500°F 25 hr	+0.03	+0.0003	1500	26.0	33.6	79.5	32.0	20.0
1500°F 50 hr	+0.03	+0.0004	1500	28.0	35.0	81.5	26.0	22.9
1500°F 50 hr	0	+0.0003	1500	--	--	--	--	--
1500°F 50 hr	+0.03	+0.0005	1500	--	--	--	--	--
1500°F 50 hr	+0.06	+0.0003	1500	--	--	--	--	--
1800°F 5 hr	+0.13	+0.0010	1800	17.0	23.0	34.0	25.0	16.8
1800°F 25 hr	+0.23	+0.0012	1800	22.0	27.1	41.0	33.0	16.9
1800°F 50 hr	+0.23	+0.0007	1800	20.2	24.8	38.3	30.0	16.5
1800°F 50 hr	+0.26	+0.0009	1800	--	--	--	--	--
1800°F 50 hr	+0.23	+0.0008	1800	--	--	--	--	--
1800°F 50 hr	+0.26	+0.0009	1800	--	--	--	--	--

TABLE IV

EFFECT OF OXIDATION EXPOSURE ON HASTELLOY C ALLOY SHEET

Test Conditions:

Oxidation Exposure = Laboratory furnace, 30 CFH shop air
Strain rates = 0.001 in./in./sec to yield
0.01 in./in./sec to rupture

Gage length = 2.0 inches
Thickness = 0.025 inch
Hold time = 5 minutes

Exposure	Change in Weight (%)	Change in Thickness (inch)	Tensile Test Temperature (°F)	Proportional Limit (Ksi)	0.2% Yield Strength (Ksi)	Ultimate Tensile Strength (Ksi)	Elongation in 2 inches (%)	Young's Modulus (10^6 psi)
None (Control)	--	--	RT	39.5	63.7	128.2	47	29.2
None (Control)	--	--	RT	30.7	62.5	128.6	45	28.2
None (Control)	--	--	RT	45.2	70.2	125.8	44	28.2
None (Control)	--	--	1500	28.0	42.1	76.0	41.0	23.4
None (Control)	--	--	1500	30.1	41.8	71.1	--	21.1
None (Control)	--	--	1800	14.0	21.0	37.2	22.5	13.5
None (Control)	--	--	1800	15.5	24.2	40.8	25.0	14.4
1200°F 7 hr	0	+0.0001	1200	38.0	48.5	98.0	41.0	24.5
1200°F 25 hr	0	+0.0001	1200	37.0	49.5	--	--	22.6
1200°F 50 hr	+0.04	+0.0007	1200	40.0	51.3	94.0	--	23.4
1200°F 50 hr	+0.08	0	1200	--	--	--	--	--
1200°F 50 hr	+0.04	+0.0004	1200	--	--	--	--	--
1200°F 50 hr	+0.04	+0.0002	1200	--	--	--	--	--
1500°F 5 hr	0	+0.0004	1500	40.5	52.0	78.9	33.0	21.4
1500°F 25 hr	0	+0.0003	1500	40.3	60.0	87.0	35.0	19.8
1500°F 50 hr	+0.04	+0.0002	1500	41.5	60.4	86.0	25.0	20.3
1500°F 50 hr	+0.04	+0.0001	1500	--	--	--	--	--
1500°F 50 hr	+0.04	+0.0005	1500	--	--	--	--	--
1500°F 50 hr	+0.04	0	1500	--	--	--	--	--
1800°F 5 hr	+0.08	+0.0005	1800	17.6	26.5	--	--	17.2
1800°F 25 hr	+0.20	+0.0006	1800	17.5	23.6	36.9	26.0	14.6
1800°F 50 hr	+0.17	+0.0004	1800	16.4	25.2	37.3	25.5	13.9
1800°F 50 hr	+0.12	+0.0005	1800	--	--	--	--	--
1800°F 50 hr	+0.21	+0.0005	1800	--	--	--	--	--
1800°F 50 hr	+0.21	+0.0005	1800	--	--	--	--	--

TABLE V

EFFECT OF OXIDATION EXPOSURE ON TYPE 316L STAINLESS STEEL SHEET

Test Conditions:

Oxidation Exposure = Laboratory furnace, 30 CFH shop air
Strain rates = 0.001 in./in./sec to yield
0.01 in./in./sec to rupture

Gage length = 2.0 inches
Thickness = 0.033 inch
Hold time = 5 minutes

Exposure	Change in Weight (%)	Change in Thickness (inch)	Tensile Test Temperature (°F)	Proportional Limit (Ksi)	0.2% Yield Strength (Ksi)	Ultimate Tensile Strength (Ksi)	Elongation in 2 inches (%)	Young's Modulus (10^6 psi)
None (Control)	--	--	RT	28.5	48.2	92.0	46	28.1
None (Control)	--	--	RT	20.7	40.9	92.4	46	27.7
None (Control)	--	--	RT	13.8	39.9	91.4	47	27.2
None (Control)	--	--	1800	6.5	9.4	18.0	42.0	6.2
None (Control)	--	--	1800	5.2	9.7	20.0	43.0	5.9
1200°F 7 hr	0	+0.0002	1200	17.0	24.1	64.0	29.0	19.0
1200°F 25 hr	-0.07	+0.0002	1200	18.0	24.5	63.7	29.0	19.4
1200°F 50 hr	-0.04	+0.0003	1200	15.0	24.0	62.5	27.0	19.8
1200°F 50 hr	0	+0.0002	1200	--	--	--	--	--
1200°F 50 hr	-0.04	+0.0002	1200	--	--	--	--	--
1200°F 50 hr	-0.04	+0.0002	1200	--	--	--	--	--
1500°F 5 hr	0	+0.0003	1500	13.7	20.4	41.1	31.0	15.9
1500°F 25 hr	+0.04	+0.0001	1500	12.5	20.3	41.3	31.0	16.4
1500°F 50 hr	0	+0.0003	1500	12.0	19.6	40.7	28.0	16.2
1500°F 50 hr	0	+0.0003	1500	--	--	--	--	--
1500°F 50 hr	0	+0.0005	1500	--	--	--	--	--
1500°F 50 hr	0	+0.0003	1500	--	--	--	--	--
1800°F 5 hr	+0.24*	+0.0009*	1800	8.3	11.4	18.9	24.0	9.8
1800°F 25 hr	+0.25	+0.0015	1800	8.0	10.0	18.3	21.5	8.5
1800°F 50 hr	+0.04	+0.0011	1800	8.6	11.2	19.5	20.0	10.0
1800°F 50 hr	+0.07	+0.0012	1800	--	--	--	--	--
1800°F 50 hr	+0.07	+0.0012	1800	--	--	--	--	--
1800°F 50 hr	-0.18	+0.0012	1800	--	--	--	--	--

* Loose green scale, some lost prior to weighing and measuring.

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TABLE VI

EFFECT OF OXIDATION EXPOSURE ON TYPE 321 STAINLESS STEEL SHEET

Test Conditions:

Oxidation Exposure = Laboratory furnace, 30 CFH shop air
Strain rate = 0.001 in./in./sec to yield
0.01 in./in./sec to rupture

Gage length = 2.0 inches
Thickness = 0.033 inch
Hold time = 5 minutes

Exposure	Change in Weight (%)	Change in Thickness (inch)	Tensile Test Temperature (°F)	Proportional Limit (Ksi)	0.2% Yield Strength (Ksi)	Ultimate Tensile Strength (Ksi)	Elongation in 2 inches (%)	Young's Modulus (10^6 psi)
None (Control)	--	--	RT	16.8	35.7	87.5	45	27.0
None (Control)	--	--	RT	16.3	32.8	88.3	48	27.6
None (Control)	--	--	1800	3.6	8.2	15.4	44.0	4.2
1200°F 5 hr	0	+0.0003	1200	21.0	27.3	54.6	22.0	18.0
1200°F 25 hr	-0.04	+0.0002	1200	20.9	28.2	54.1	21.5	20.3
1200°F 50 hr	-0.04	+0.0002	1200	20.1	28.2	53.0	22.0	20.0
1200°F 50 hr	-0.04	+0.0001	1200	--	--	--	--	--
1200°F 50 hr	-0.04	+0.0002	1200	--	--	--	--	--
1200°F 50 hr	-0.04	+0.0004	1200	--	--	--	--	--
1500°F 5 hr	+0.04	+0.0004	1500	12.0	20.0	32.6	29.5	15.8
1500°F 25 hr	0	+0.0003	1500	10.0	16.9	30.0	30.0	12.9
1500°F 50 hr	0	+0.0003	1500	11.5	17.0	33.1	27.0	13.5
1500°F 50 hr	0	-0.0005	1500	--	--	--	--	--
1500°F 50 hr	+0.04	+0.0005	1500	--	--	--	--	--
1500°F 50 hr	0	+0.0005	1500	--	--	--	--	--
1800°F 5 hr	-0.34*	+0.0012*	1800	4.8	7.4	14.7	35.0	10.0
1800°F 25 hr	+0.34	+0.0011	1800	5.6	7.6	14.1	28.0	6.9
1800°F 50 hr	+0.30	+0.0009	1800	5.2	8.0	14.7	24.0	6.0
1800°F 50 hr	+0.45	+0.0012	1800	--	--	--	--	--
1800°F 50 hr	+0.37	+0.0012	1800	--	--	--	--	--
1800°F 50 hr	+0.41	+0.0013	1800	--	--	--	--	--

* Loose black scale, some scale lost prior to weighing and measuring.

TABLE VII

EFFECT OF OXIDATION EXPOSURE ON 6061-T6 ALUMINUM SHEET

Test Conditions:

Oxidation exposure = Circulating air, Lindberg aging furnace
Tensile strain rates = 0.001 in./in./sec to yield
0.01 in./in./sec to rupture

Gage length = 2.0 inches
Thickness = 0.032 inch
Hold time = 5 minutes

Exposure	Change in Weight (%)	Change in Thickness (inch)	Tensile Test Temperature (°F)	Proportional Limit (Ksi)	0.2% Yield Strength (Ksi)	Ultimate Tensile Strength (Ksi)	Elongation in 2 inches (%)	Young's Modulus (10^6 psi)
None (Control)	--	--	RT	26.8	37.9	43.3	10	10.8
None (Control)	--	--	RT	29.8	38.3	43.0	10	10.4
None (Control)	--	--	RT	27.5	37.0	42.7	9.5	10.2
None (Control)	--	--	350	28.4	35.0	37.4	9.0	9.3
None (Control)	--	--	500	16.5	23.2	25.8	8.6	8.6
None (Control)	--	--	500	18.1	24.0	26.7	8.5	8.0
350°F 5 hr	0	-0.0002	350	23.9	33.0	35.5	7.5	9.5
350°F 25 hr	0	-0.0003	350	26.0	33.1	35.4	8.0	9.2
350°F 50 hr	0	-0.0001	350	24.0	33.2	35.3	8.0	9.4
350°F 50 hr	0	0	350	--	--	--	--	--
350°F 50 hr	0	-0.0001	350	--	--	--	--	--
350°F 50 hr	0	0	350	--	--	--	--	--
500°F 5 hr	0	-0.0003	500	13.2	18.5	20.4	9.0	7.9
500°F 25 hr	-0.1	-0.0002	500	10.6	14.5	16.5	11.5	7.0
500°F 50 hr	+0.1	-0.0006	500	10.8	14.2	16.5	12.0	7.8
500°F 50 hr	0	-0.0001	500	--	--	--	--	--
500°F 50 hr	-0.1	-0.0003	500	--	--	--	--	--
500°F 50 hr	0	-0.0001	500	--	--	--	--	--
650°F 5 hr	0	-0.0005	650	3.4	5.9	7.2	16.0	3.9
650°F 25 hr	0	-0.0002	650	2.9	5.1	6.4	17.0	3.5
650°F 50 hr	0	-0.0001	650	2.2	5.0	6.0	16.0	3.5
650°F 50 hr	0	-0.0004	650	--	--	--	--	--
650°F 50 hr	0	-0.0002	650	--	--	--	--	--
650°F 50 hr	0	-0.0001	650	--	--	--	--	--

TABLE VIII

EFFECT OF OXIDATION EXPOSURE ON A110AT TITANIUM SHEET

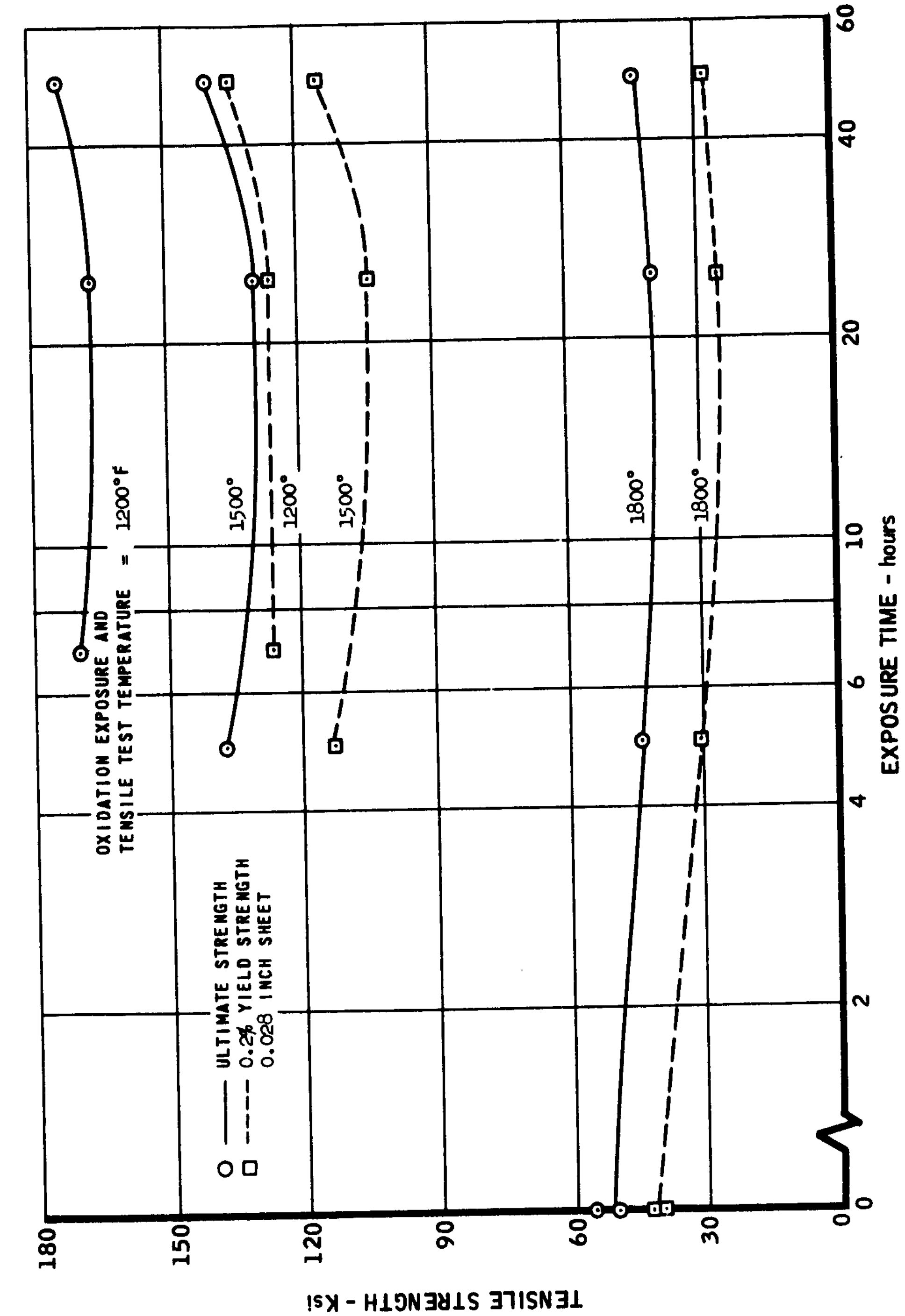
Test Conditions:

Oxidation Exposure = Laboratory furnace, 30 CFH shop air
Strain rates = 0.001 in./in./sec to yield
0.01 in./in./sec to rupture

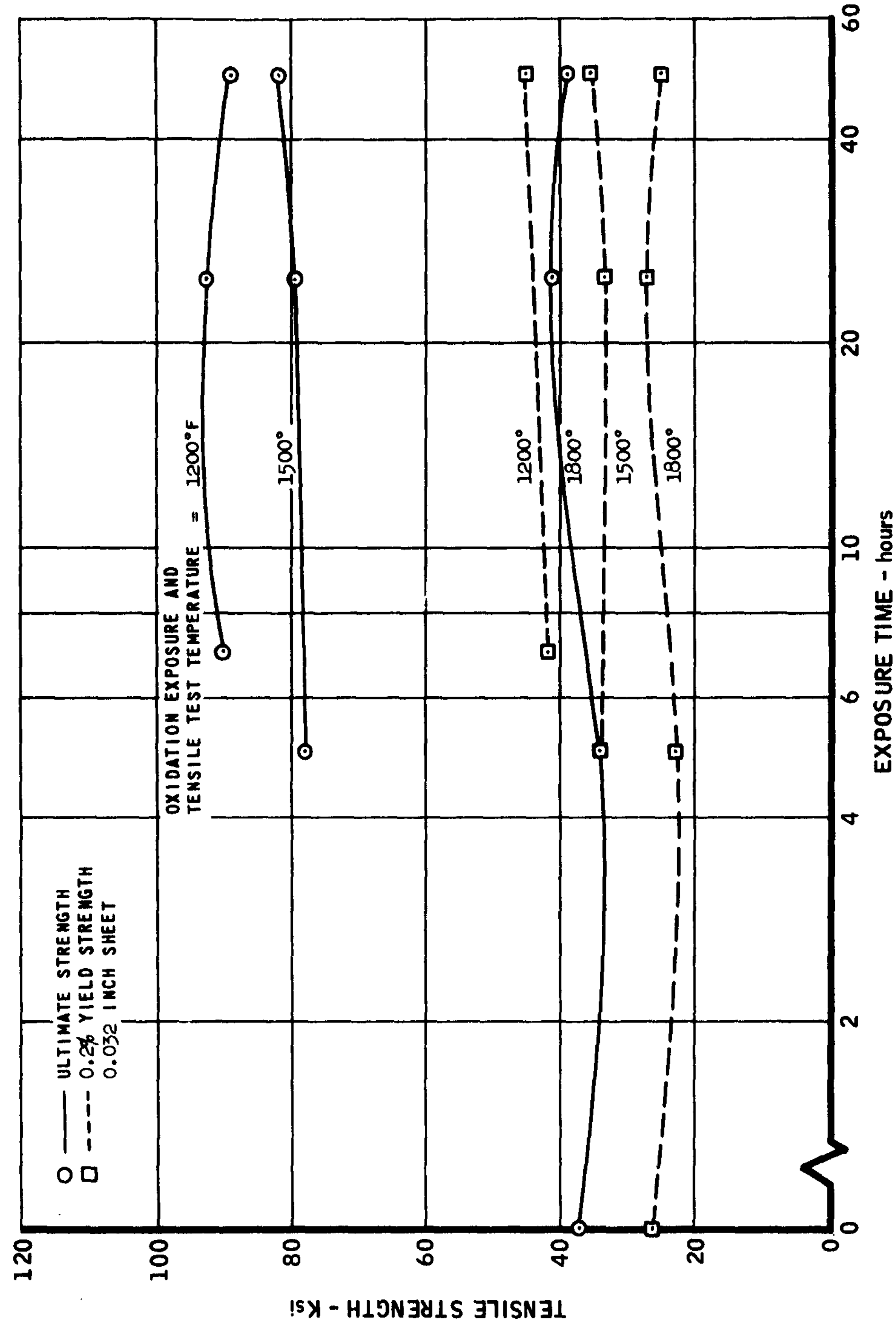
Gage length = 2.0 inches
Thickness = 0.033 inch
Hold time = 5 minutes

Exposure	Change in Weight (%)	Change in Thickness (inch)	Tensile Test Temperature (°F)	Proportional Limit (Ksi)	0.2% Yield Strength (Ksi)	Ultimate Tensile Strength (Ksi)	Elongation in 2 inches (%)	Young's Modulus (10^6 psi)
None (Control)	--	--	RT	99.7	115.1	125.8	13.5	16.6
None (Control)	--	--	RT	89.3	115.6	126.6	14.0	16.4
None (Control)	--	--	1200	18.5	38.2	55.0	25.5	8.4
800°F 5 hr	0	+0.0001	800	46.0	56.7	75.0	17.5	12.6
800°F 25 hr	0	0	800	49.0	57.4	75.0	17.0	12.8
800°F 50 hr	0	+0.0005	800	48.1	58.0	75.0	17.0	12.8
800°F 50 hr	0	+0.0001	800	--	--	--	--	--
800°F 50 hr	+0.1	+0.0004	800	--	--	--	--	--
800°F 50 hr	0	0	800	--	--	--	--	--
1000°F 5 hr	+0.1	+0.0001	1000	40.1	51.5	65.5	17.5	11.4
1000°F 25 hr	+0.1	0	1000	35.0	50.0	64.0	17.5	11.3
1000°F 50 hr	+0.1	+0.0002	1000	36.0	50.0	64.0	18.5	11.5
1000°F 50 hr	0	+0.0001	1000	--	--	--	--	--
1000°F 50 hr	+0.1	+0.0002	1000	--	--	--	--	--
1000°F 50 hr	0	-0.0003	1000	--	--	--	--	--
1200°F 5 hr	+0.1	+0.0004	1200	14.5	38.0	52.7	24.0	8.4
1200°F 25 hr	+0.1	+0.0001	1200	11.0	37.9	53.1	24.0	9.0
1200°F 50 hr	+0.25	+0.0002	1200	15.5	40.4	57.0	20.0	9.7
1200°F 50 hr	+0.25	+0.0004	1200	--	--	--	--	--
1200°F 50 hr	+0.3	-0.0002	1200	--	--	--	--	--
1200°F 50 hr	+0.25	+0.0001	1200	--	--	--	--	--

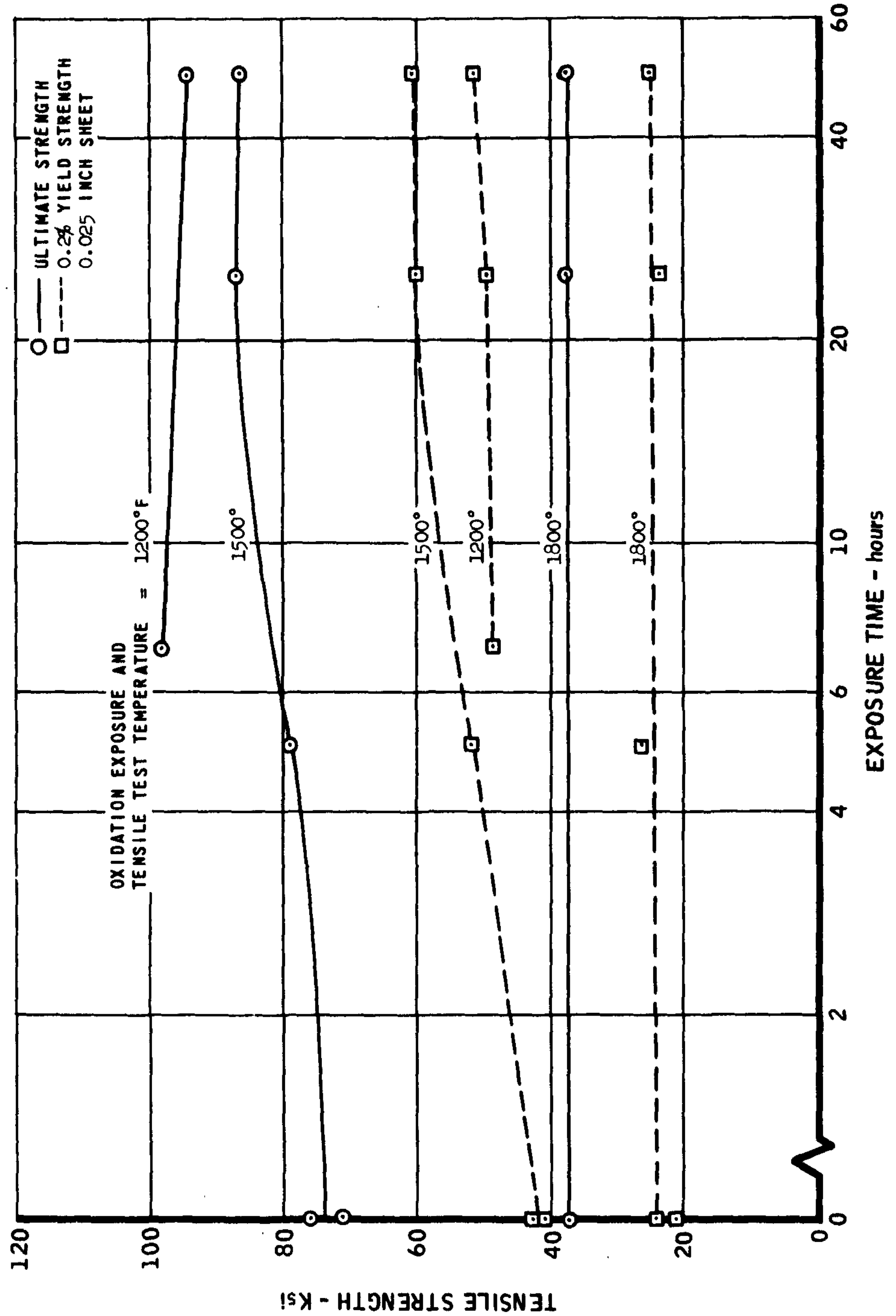
EFFECT OF OXIDATION EXPOSURE AND AGING ON THE TENSILE PROPERTIES OF RENE' 41 ALLOY SHEET



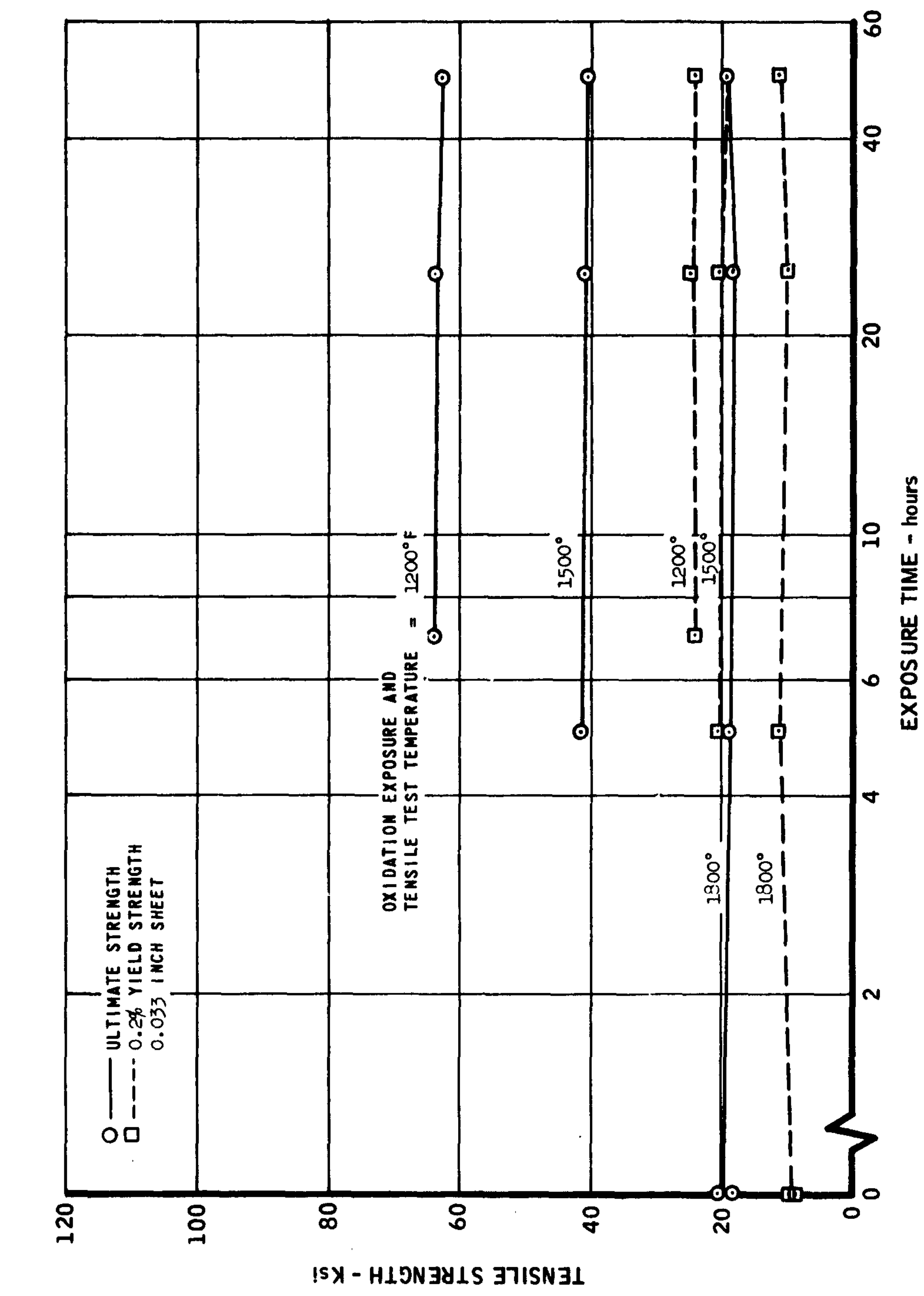
EFFECT OF OXIDATION EXPOSURE AND AGING ON THE TENSILE PROPERTIES OF L-605 ALLOY SHEET



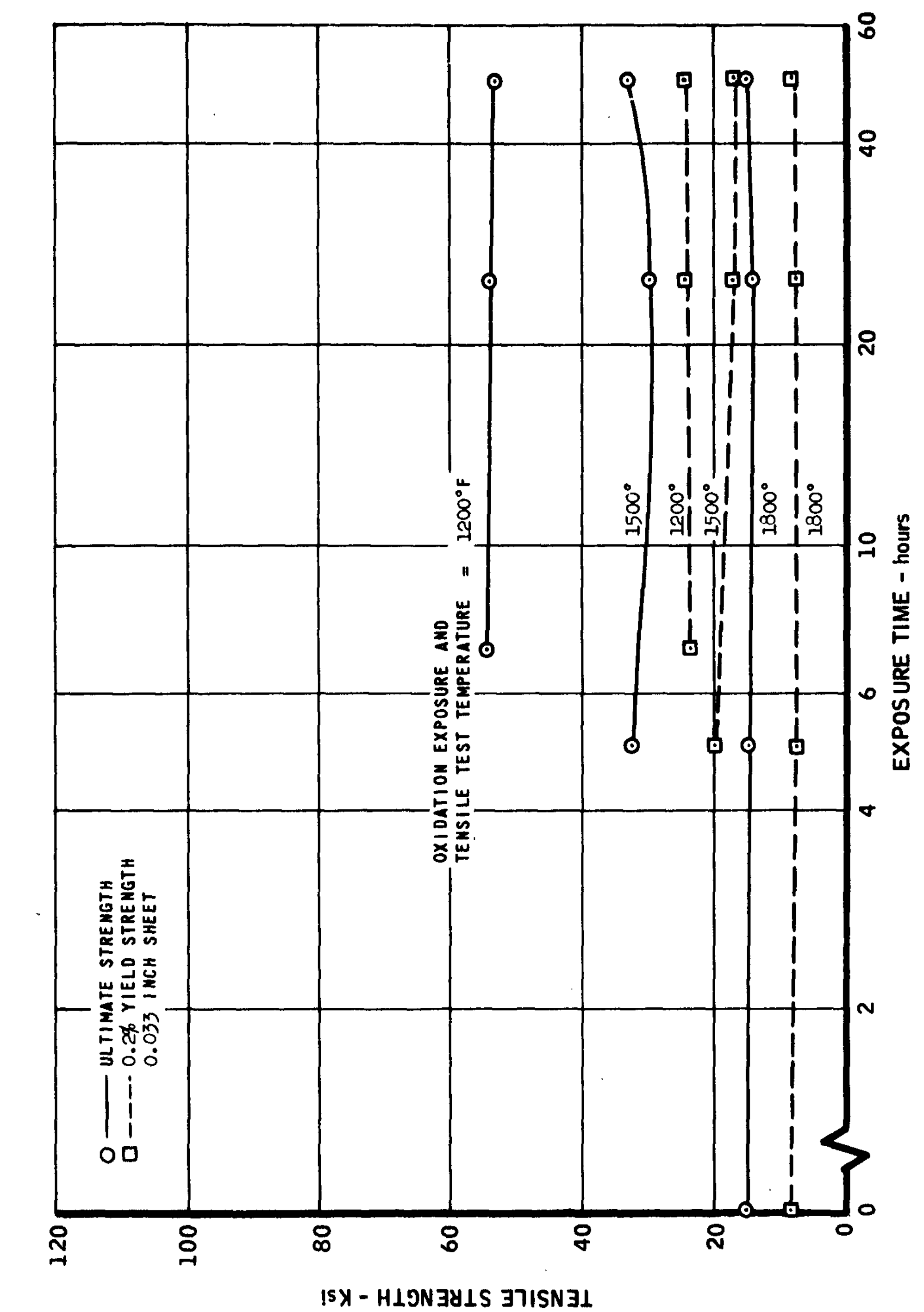
EFFECT OF OXIDATION EXPOSURE AND AGING ON THE TENSILE PROPERTIES OF HASTELLOY C ALLOY SHEET



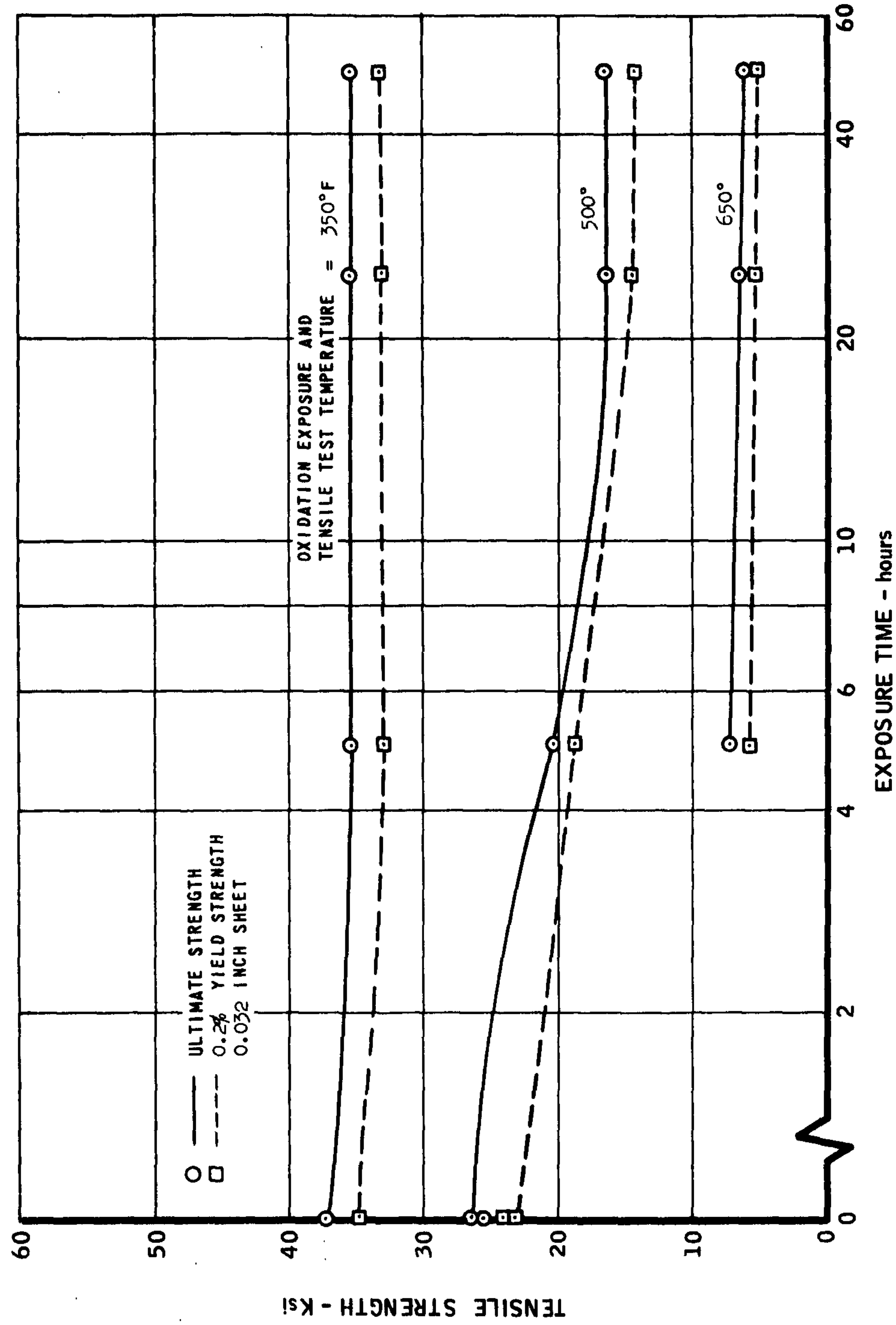
EFFECT OF OXIDATION EXPOSURE AND AGING ON THE TENSILE PROPERTIES OF TYPE 316 L STAINLESS STEEL SHEET



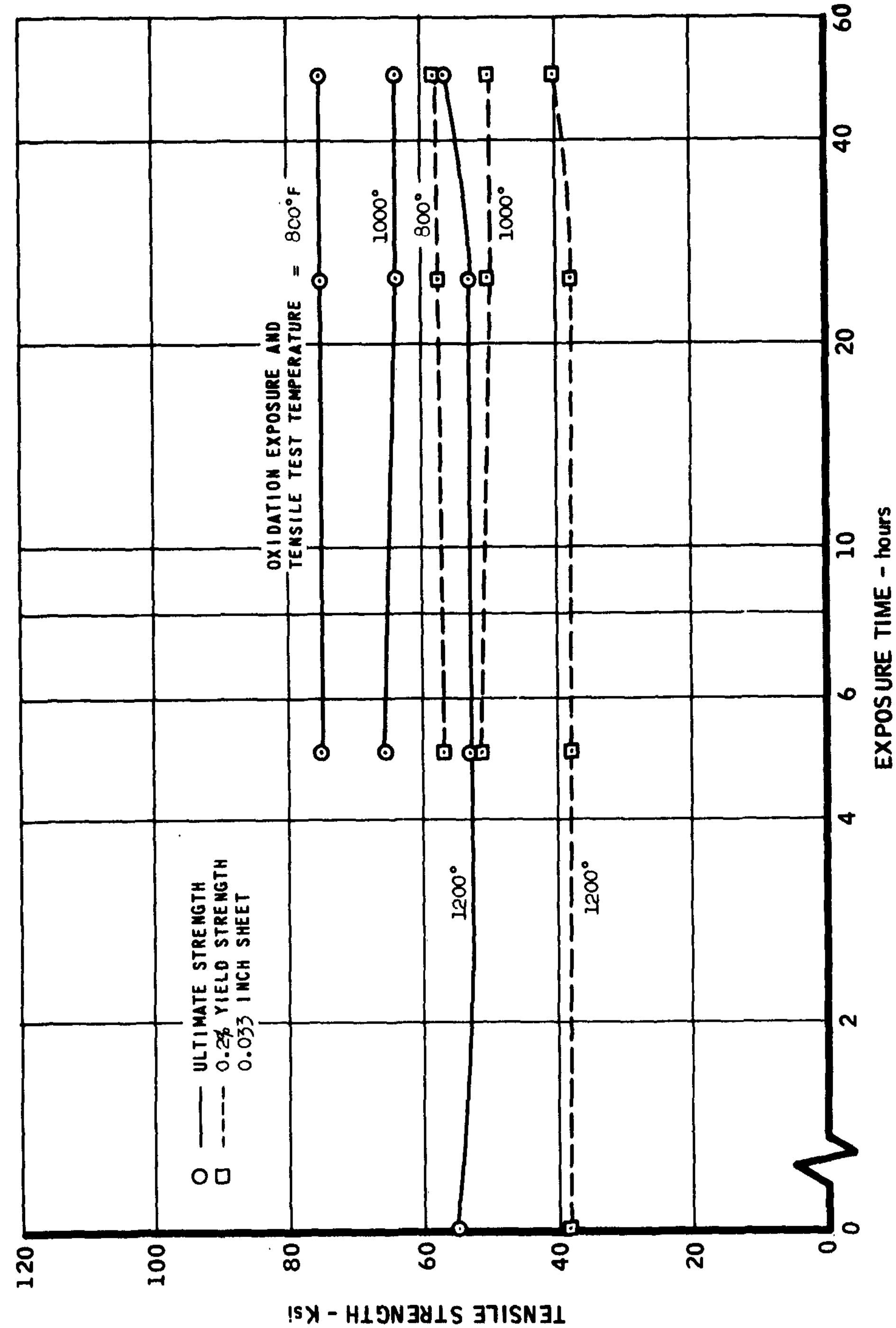
EFFECT OF OXIDATION EXPOSURE AND AGING ON THE TENSILE PROPERTIES OF TYPE 321 STAINLESS STEEL SHEET

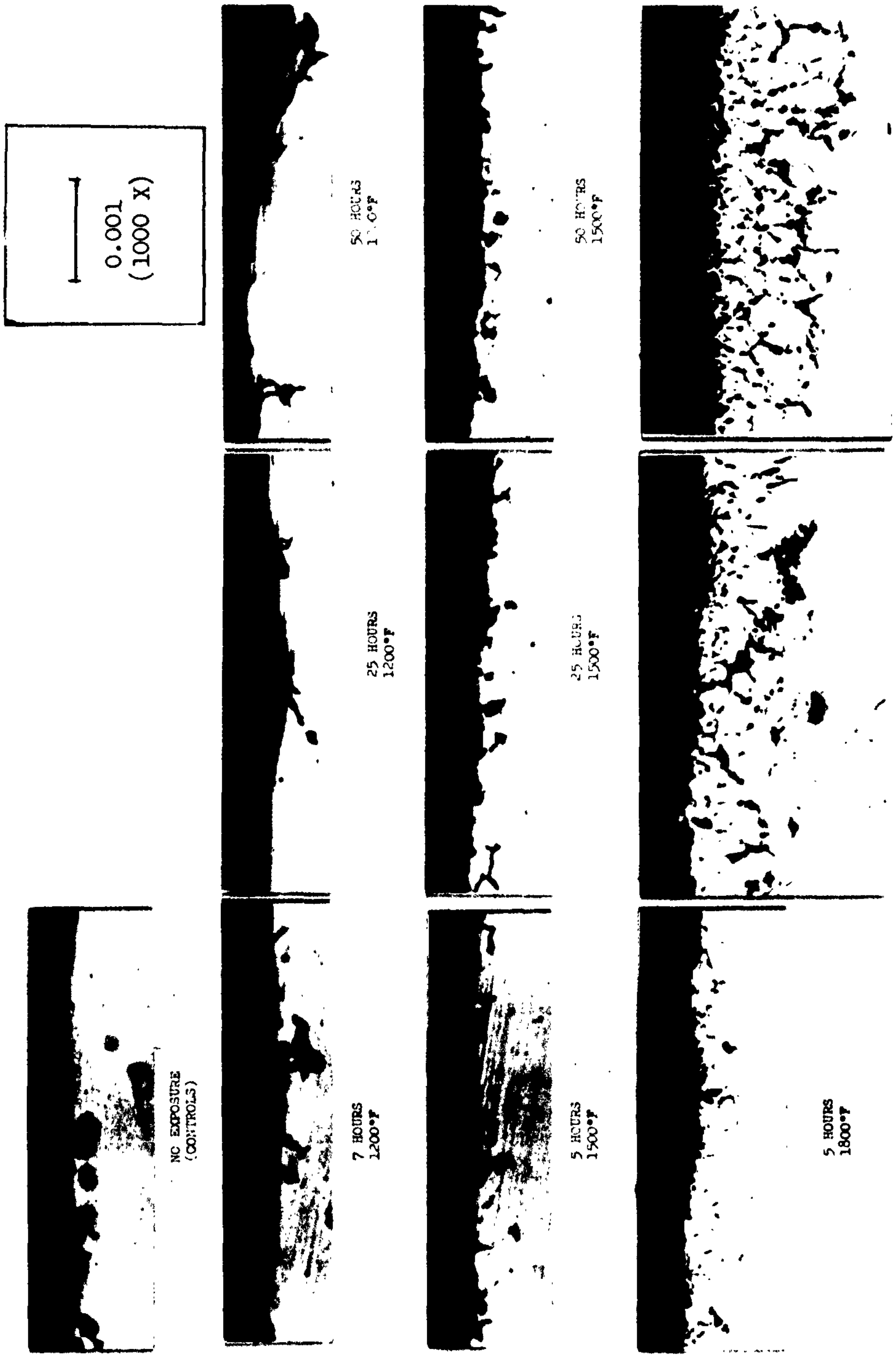


EFFECT OF OXIDATION EXPOSURE AND AGING ON THE TENSILE PROPERTIES OF 6061-T6 ALUMINUM SHEET



EFFECT OF OXIDATION EXPOSURE AND AGING ON THE TENSILE PROPERTIES OF A110AT TITANIUM SHEET

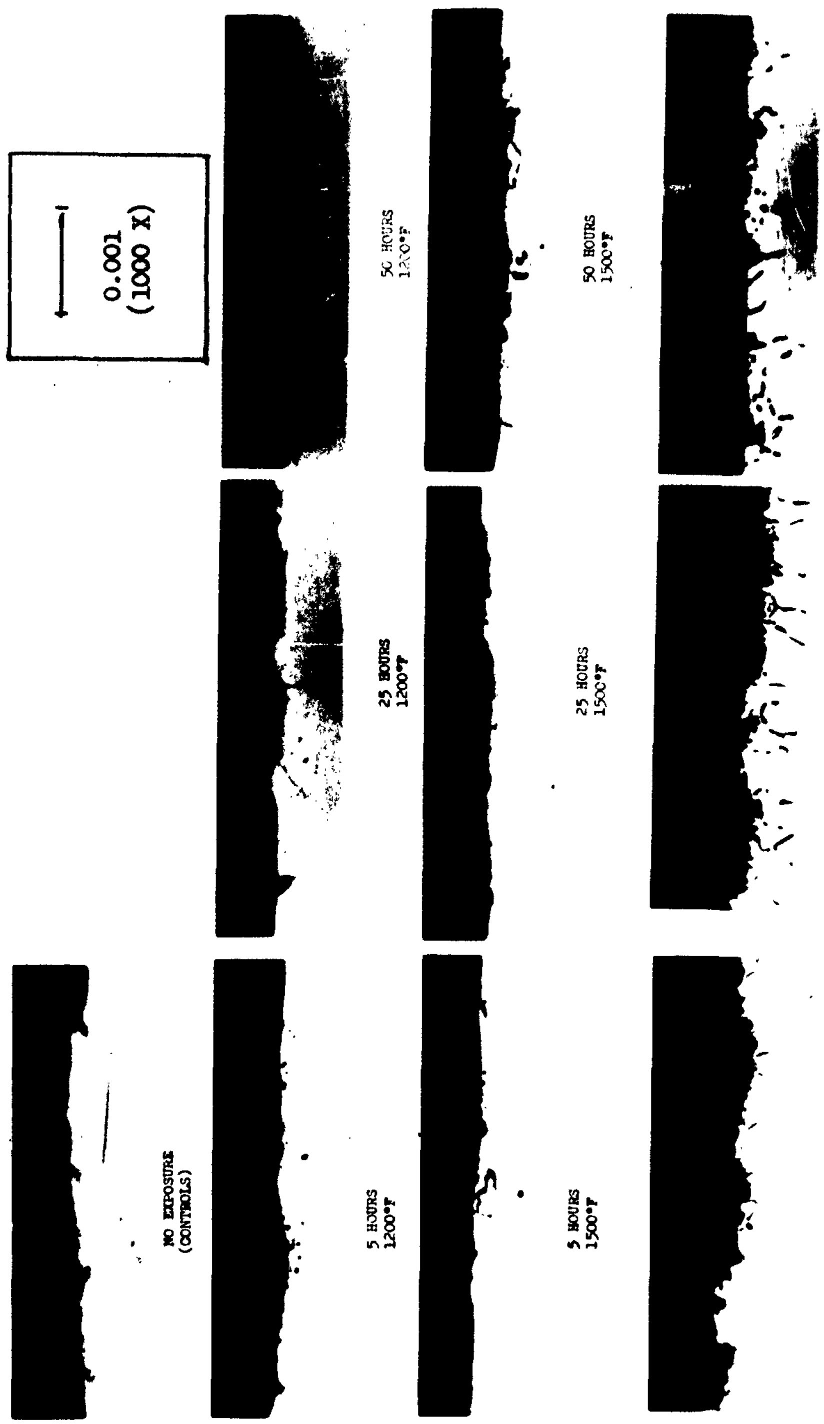




C 4369-4

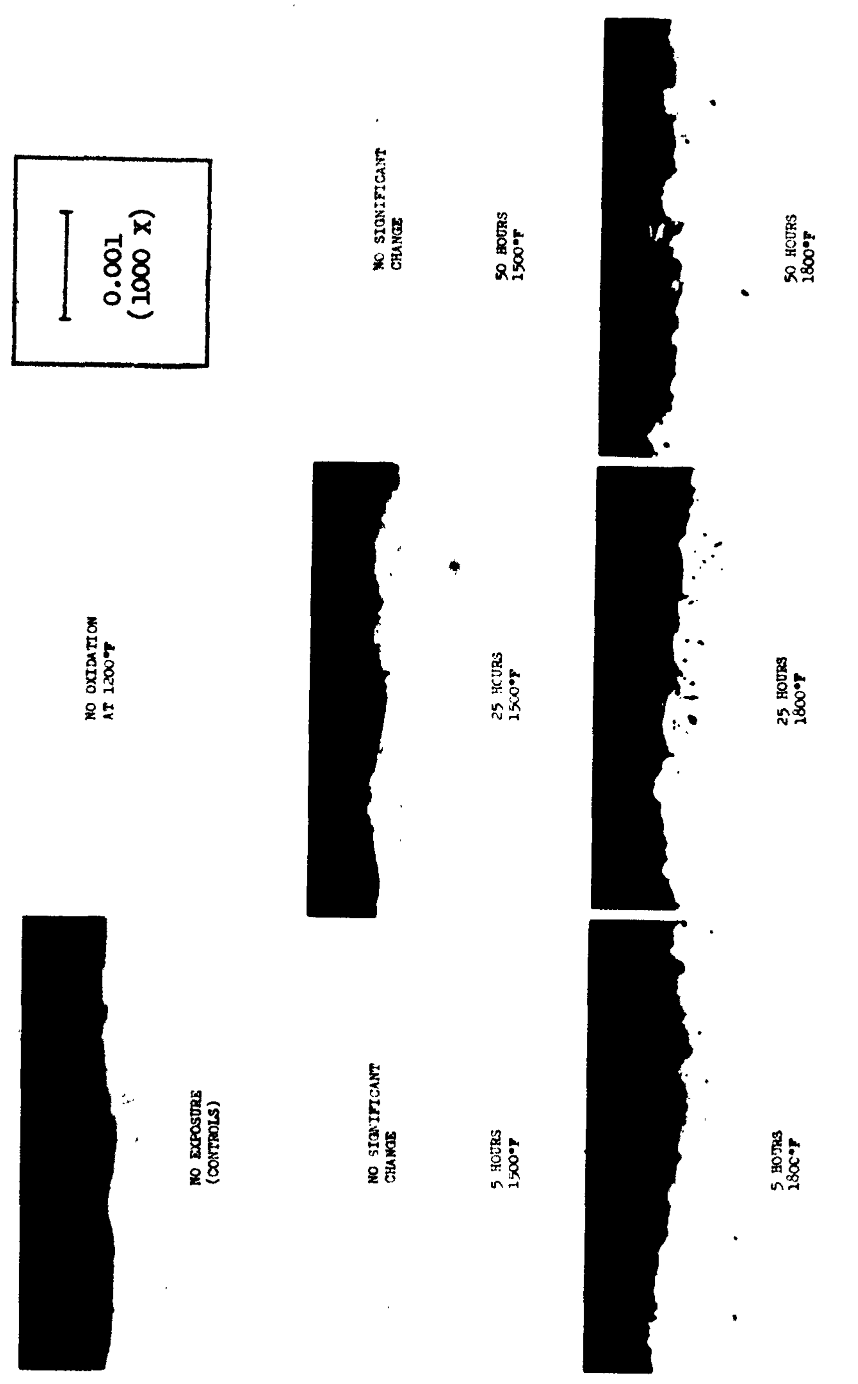
FIGURE 8 - Photomicrographs of Rene' 41 Alloy Sheet After Oxidation Exposure

MAC A673



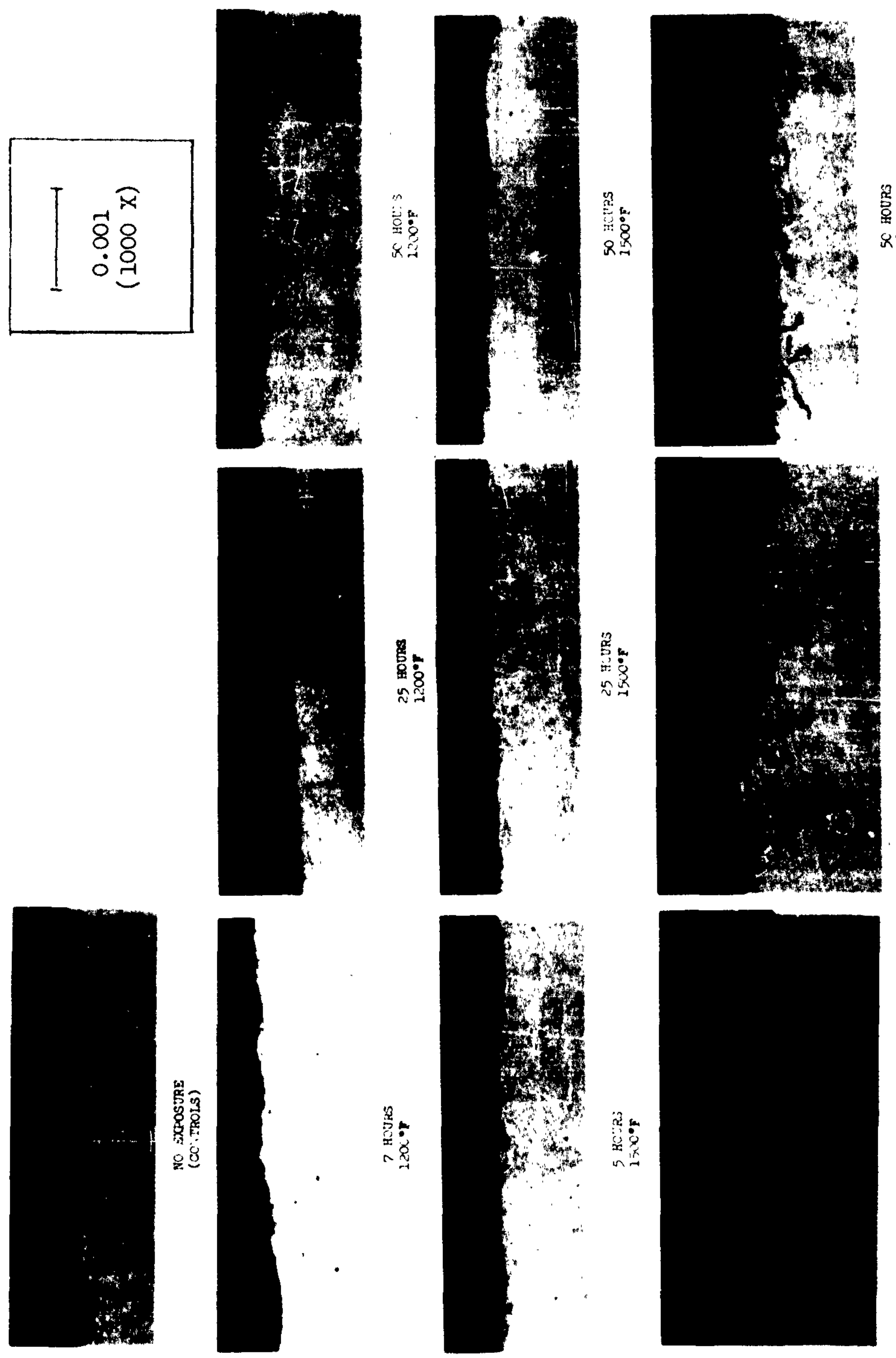
C 4369-5

FIGURE 9 - Photomicrographs of L-605 Alloy Sheet After Oxidation Exposure

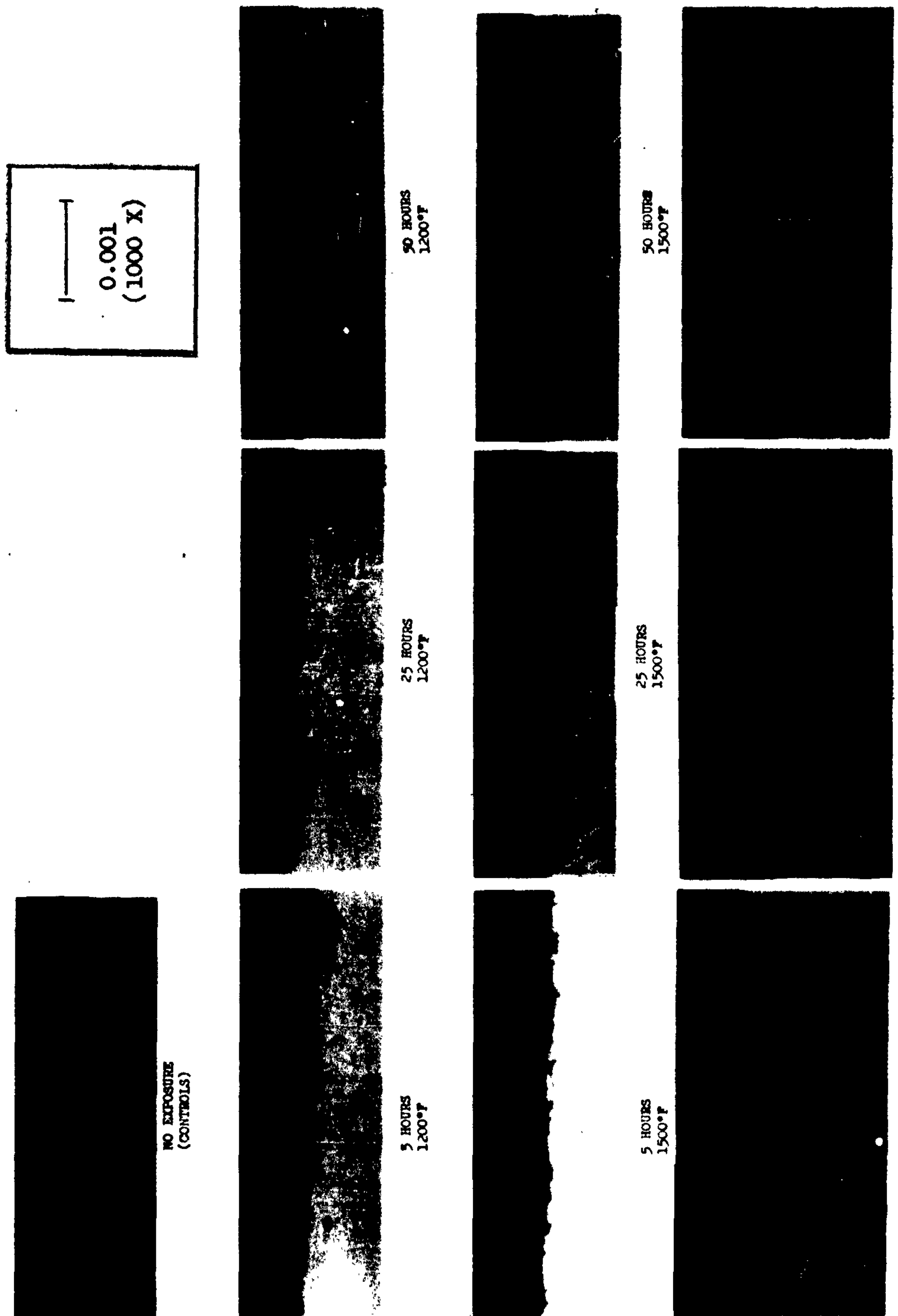


C 4369-7

FIGURE 10 - Photomicrographs of Hastelloy C Sheet After Oxidation Exposure



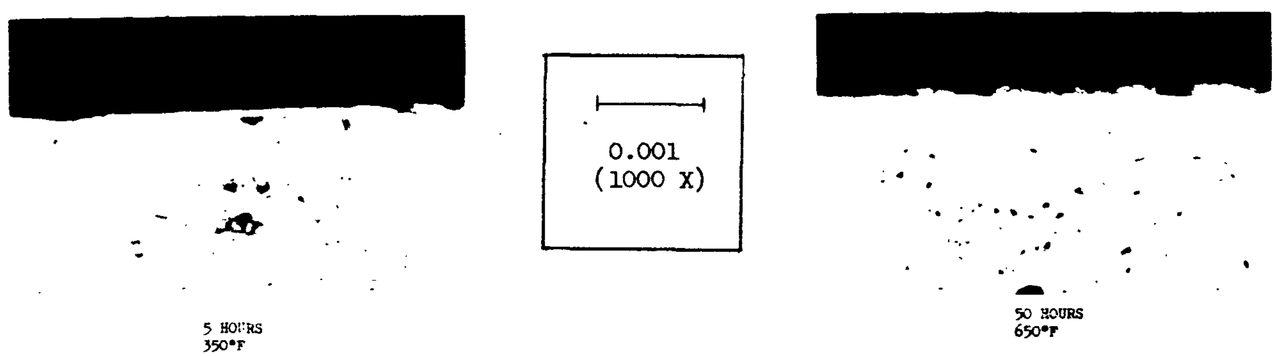
C 4369-3
FIGURE 11 - Photomicrographs of Type 316L Stainless Steel Sheet After Oxidation Exposure



C 4369-6

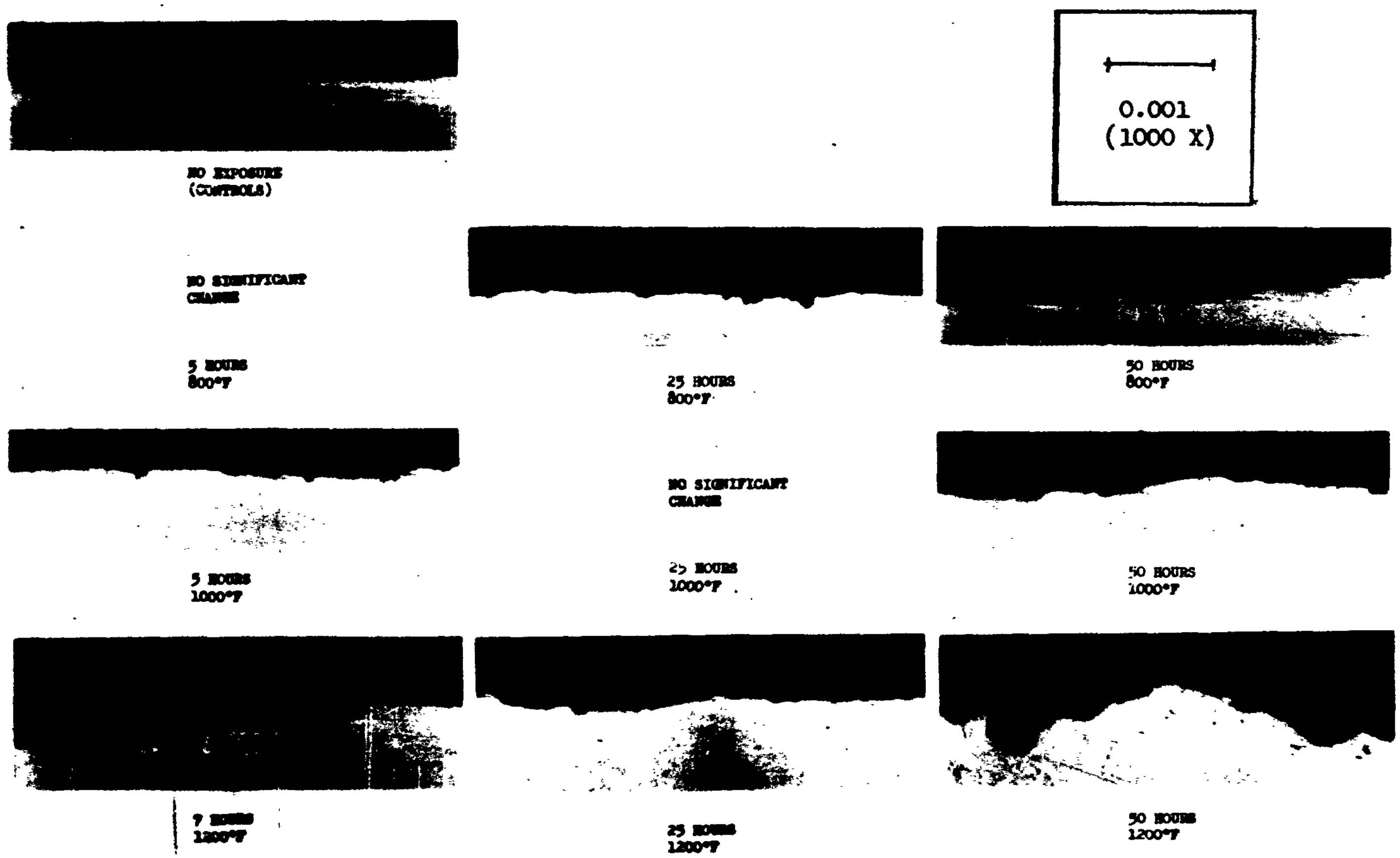
FIGURE 12 - Photomicrographs of Type 321 Stainless Steel Sheet After Oxidation Exposure

MAC A673



C 4369-1

FIGURE 13 - Photomicrographs of 6061-T6 Aluminum Sheet After Oxidation Exposure



C 4369-2

FIGURE 14 - Photomicrographs of A110AT Titanium Sheet after Oxidation Exposure

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